Disorder and flux pinning in superconducting pnictide single crystals

C.J. van der Beek[1], G. Rizza[1], M. Konczykowski[1], P. Fertey[2], I. Monnet[3], R. Okazaki[4], T. Kato[4], K. Hashimoto[4], M. Shimozawa[4], H. Shishido[4], M. Yamashita[4], M. Ishikado[5], H. Kito[6], A. Iyo[6], H. Eisaki[6], S. Shamoto[5], T. Shibauchi[4], and Y. Matsuda[4]

[1] *Laboratoire des Solides Irradiés, CNRS UMR 7642 & CEA-DSM-IRAMIS, Ecole Polytechnique, 91128 Palaiseau, France*
[2] *Synchrotron SOLEIL, L'Orme des Merisiers, Saint-Aubin - BP 48, F-91192 Gif-sur-Yvette cedex, France*
[3] *CIMAP, 6 boulevard du Marchal Juin, F-14050 Caen cedex 4, France*
[4] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[5] *Quantum Beam Science Directorate, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 319-1195, Japan*
[6] *Nanoelectronics Research Institute (NeRI), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Central 2, Tsukuba, Ibaraki 305-8568, Japan*

Abstract

Crystalline disorder in the pnictide superconductor $PrFeAsO_{1-y}$ is studied using magneto-optical visualisation of flux penetration, Transmission Electron Microscopy, and X-ray diffraction using synchrotron radiation. Critical-state like flux distributions and the magnitude and temperature dependence of the critical current demonstrate bulk vortex pinning by oxygen vacancies at all temperatures.

Key words: iron-pnictide superconductors, flux pinning, crystalline disorder

Recently, strongly disordered vortex ensembles have been imaged in pnictide superconductors using small-angle neutron scattering [1], Bitter decoration [1], and scanning tunneling spectroscopy [2]. Such disorder in the vortex lattice is indicative of pinning by crystalline disorder [3]. This, in turn, may be responsible for strong electronic scattering, possibly affecting the superconducting ground state. Moreover, vortex pinning and disorder affect thermodynamic quantities such as the magnetization or specific heat [4]. It is therefore important to identify the defect structures responsible for vortex pinning in pnictide superconductors.

In the following, we concentrate on underdoped crystals of the $PrFeAsO_{1-y}$ phase ($y \sim 0.1$), grown by a high-pressure method [5]. Crystals were characterized using the magneto-optical imaging (MOI) [6]. Differential magneto-optical (DMO) imaging was performed by subtracting a series of 10 images obtained with an applied magnetic field H_a from another 10 images obtained with $H_a + \Delta H_a$. Three crystals were further characterized by X-ray diffraction using 28.3 keV (0.43811 Å) radiation on the CRISTAL beam at the SOLEIL synchrotron. Images of diffraction spots were collected on a 2D CCD detector when the sample was rotated around an axis in the *ab* plane. From the 360 measured images, each corresponding to an oscillation of 1° of the crystal, layers of the reciprocal space were numerically reconstructed. Finally, a number of crystals were embedded in Si, thinned down, and studied using Transmission Electron Microscopy (TEM).

Fig. 1 shows magnetic flux penetration into a $PrFeAsO_{1-y}$ crystal. Critical state-like flux distributions

are observed at all temperatures, attesting to the importance of vortex pinning. From the calibrated intensity profiles, we extract the critical current density

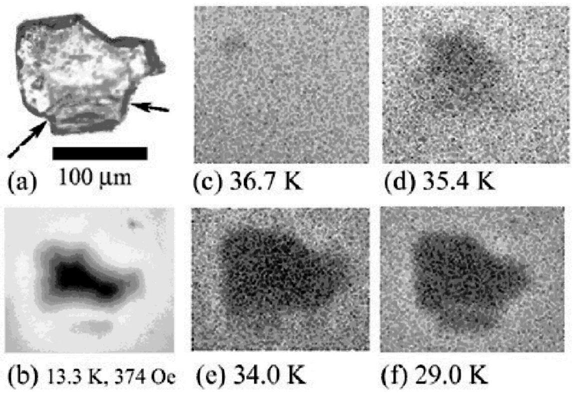

Figure 1: (a) Polarized light image of a $PrFeAsO_{1-y}$ bicrystal; the grain boundary is indicated by the two arrows. (b) MOI of critical state-like flux penetration, at 13.3 K and $H_a = 374$ Oe. Bright and dark areas correspond to high and low magnetic flux density, respectively. (c-f) DMO images of the progressive exclusion of a field modulation $\Delta H_a = 1$ Oe as temperature is lowered through the superconducting transition.

j_c, plotted in Fig. 2b. DMO imaging with a modulation $\Delta H_a = 1$ Oe, the results of which are depicted in Fig. 1c-f, reveals significant heterogeneity of T_c, presumably related to local variations of O-content. The local permeability, extracted from DMO and shown in Fig. 2a, shows that T_c variations can amount to $\Delta T_c \sim 3-4$ K within the same crystal. However, local transitions are sharp.

j_c varies from crystal to crystal, but is typically of the order $\sim 2 \times 10^9$ Am^{-2} at low T. Using the expressions from weak collective pinning theory [7], and the parameters characterizing superconductivity in $PrFeAsO_{1-y}$ [5], this is consistent with collective pinning in the single vortex limit, with a longitudinal vortex lattice correlation length $L_c = 20$ nm. Assuming pinning by quasi-particle mean-free path fluctuations induced by oxygen vacancies, the magnitude of j_c is reproduced for a density corresponding to 9×10^{-2} O vacancies per unit cell, in very good agreement with the nominal oxygen deficiency, $y = 0.1$ [5]. The temperature dependence of j_c is also reasonably reproduced.

Deviations from the collective pinning behaviour are observed above 20-25 K. This is due to strong pinning by disorder such as revealed by TEM. This includes (Fig. 3) buckling of the FeAs layers, as well as the presence of extended pointlike defects with a typical dimension of 2 – 6 nm. The distance between defects varies between 20 – 200 nm, depending on the investigated zone. Undulation of the FeAs layers is confirmed by X-ray diffraction; typically, a mosaic spread of 4 – 5° is observed. The strongest effect on pinning is expected from the pointlike inclusions; a defect density of $\sim 1 \times 10^{20}$ m^{-3} is sufficient to explain the observed strong background pinning.

Summarizing, vortex pinning in underdoped single crystals of the iron pnictide superconductor $PrFeAsO_{1-y}$ is fairly well described assuming pinning by quasi-particle mean-free fluctuations induced by oxygen deficiency. The role of scattering by dopant atoms is therefore also expected to affect other superconducting properties.

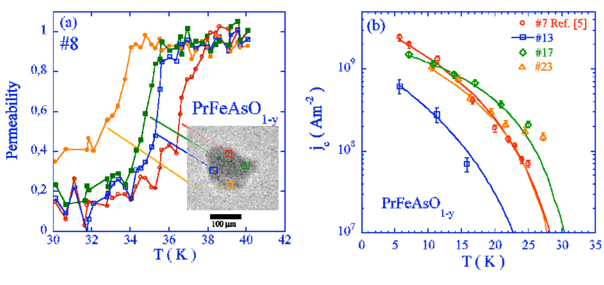

Figure 2: (a) Plot of the local permeability for four different areas of the $PrFeAsO_{1-y}$ crystal, extracted from the DMO images in Figure 1. (b) $j_c(T, H_a = 0)$ for four different $PrFeAsO_{1-y}$ crystals. Drawn lines show the temperature dependence expected for weak collective pinning [3, 7].

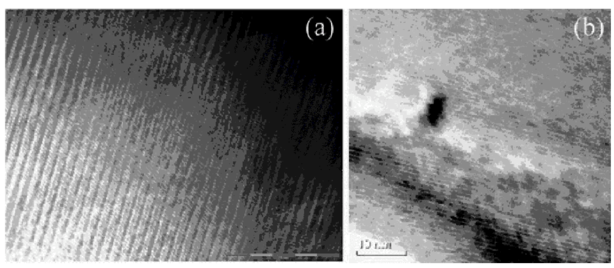

Figure 3: (a) High resolution TEM image of a $PrFeAsO_{1-y}$ crystal; an undulation of the FeAs layers can be observed. (b) TEM image showing strong contrast, interpreted as an extended point defect.

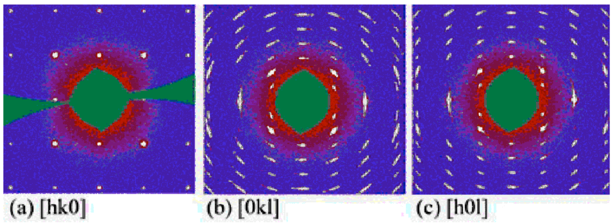

Figure 4: Cross-sections of reciprocal space, obtained on crystal # 7, used in Ref. [5]. (a) [hk0], showing good order in the FeAs plane (b) [0kl] (c) [h0l]

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